

# Results and prospects of dark matter searches with ANTARES

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## Abstract

Dark matter is one of the most important scientific goals for neutrino telescopes. These instruments have particular advantages with respect to other experimental approaches. Compared to direct searches, the sensitivity of neutrino telescopes to probe the spin-dependent cross section of WIMP-proton is unsurpassed. On the other hand, neutrino telescopes can look for dark matter in the Sun, so a potential signal would be a strong indication of dark matter, contrary to the case of other indirect searches like gammas or cosmic rays, where more conventional astrophysical interpretations are very hard to rule out. We present here the results of a binned search for neutralino annihilation in the Sun using data gathered by the ANTARES neutrino telescope during 2007-2008. These result include limits on the neutrino and muon flux and on the spin-dependent and spin-independent cross section of the WIMP-proton scattering.

*Keywords:* dark matter, WIMP, neutralino, neutrino telescopes

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## 1. Introduction

Dark matter existence has been soundly proofed by different experimental evidence, including the observations from Planck [1], the results on the Big Bang Nucleosynthesis [2], the rotation curves of galaxies [3] and the studies of highly red-shifted Ia supernovae [4]. These results show that the only about 30% of the content of the Universe is matter and about 70% is dark energy. Moreover, 85% of the matter is non-barionic. Explanations for the nature of

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this non-barionic component have to be outside the Standard Model. The basic conditions required to a particle dark matter candidate are to have interaction cross section of the order of that of the weak interaction and to be massive and stable. Particles like neutrinos, which fulfill these requirement for a good dark matter candidate, are not viable as a dominant component, since they are relativistic and cannot explain the large-scale structure of the Universe. Given these conditions, a generic family of particles fulfilling these conditions are called WIMPs (Weakly Interacting Massive Particles). The most popular model which provides WIMP candidates is Supersymmetry (SUSY). In particular, in this analysis we have looked for neutralinos, which in many of the possible scenarios is the lightest SUSY particle. Its stability is preserved by the conservation of the R-parity. The results have been analyzed with respect to two implementations of the SUSY framework: CMSSM [5] and MSSM-7 [6].

The analysis presented here is a binned search for neutrinos produced after the neutralino annihilations in the Sun direction using 2007-2008 data of the ANTARES neutrino telescope, since neutralinos would accumulate in massive objects like the Sun and their annihilation would produce high energy neutrinos [7]. One of the advantages of this kind of searches, compared to other indirect searches like looking for gammas in the Galactic Center or excesses of positrons is that a potential signal would be a very robust indication of dark matter, since no other astrophysical explanations are expected.

The structure of this paper is as follows. The ANTARES detector is introduced in Section 2. The estimations for signal and background are described in Section 3. Section 4 explains the optimization procedure. Finally, the results are presented in Section 5 and the conclusions are summarized in Section 6.

## 2. The ANTARES detector

The ANTARES neutrino telescope [8] is located in the Mediterranean Sea, at a depth of 2.5 km, about 40 km off Toulon, in the French coast. It consists of 885 photomultipliers (PMTs) arranged in a three-dimensional array. The operation principle is based on the detection by these PMTs of the Cherenkov light induced by relativistic muons produced in CC interaction of high energy neutrinos in the surroundings of the detector. The PMTs are installed along 12 lines anchored to the sea floor and kept taut by buoys at the top of them. The length of the lines is 450 m and the distance between

lines is 60-75 m. The PMTs are grouped in triplets in order to reduce the effect of optical background produced by potassium-40 and bioluminescence. The position and time information of the photons detected by the PMTs can be used to reconstruct the muon direction.

The installation of the detector was completed in 2008, although during 2007 five lines were already installed and produced data which can be used for physics analysis.

### 3. Signal and background estimation

The signal, i.e. the neutrino flux arriving at Earth from neutralino annihilations in the Sun, is calculated using the WimpSim package [9] for the relevant channels in this analysis ( $q\bar{q}$ ,  $l\bar{l}$ ,  $W^+$ ,  $W^-$ ,  $ZZ$ , Higgs doublets  $\phi\phi^*$  and  $\nu\bar{\nu}$ ) for energies ranging from 10 GeV to 10 TeV. As benchmarks for describing the range of potential signal, three channels have been analyzed:  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow b\bar{b}$  (soft channel) and  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-$  and  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tau^+\tau^-$  (hard channels). In each case, a 100% branching ratio is assumed to represent the most extreme cases in the parameter space. Oscillations among the three neutrino flavours,  $\nu$  absorption and  $\tau$  regeneration in the Sun's medium are taken into account by WimpSim.

There are two kinds of background for detectors like ANTARES. First the muons produced by cosmic rays interacting in the atmosphere. In order to reduce this kind of background, only upgoing event are selected, since muons cannot traverse the Earth. However, some of these muons (a small fraction of the total but a large number given the flux involved) are misreconstructed as upgoing. This is why further cuts are needed on the quality of the reconstructed track in order to reject them. The second kind of background are the atmospheric neutrinos, also produced in the cosmic ray interactions in the atmosphere. This is an irreducible background. The background estimation is done by scrambling real data, which reduces the impact of systematic uncertainties.

### 4. Optimization

The procedure for the analysis presented here has followed a blind strategy in order to avoid selection biases. This means that the cuts have been selected before looking at the source region. The criterion to choose the cuts

has been to optimize (minimize) the average upper limit which can be set for any given neutralino mass. This average upper limit can be calculated as

$$\overline{\Phi}_{\nu_{\mu}+\bar{\nu}_{\mu}} = \frac{\bar{\mu}^{90\%}}{\sum_i \bar{A}_{\text{eff}}^i(M_{\text{WIMP}}) \times T_{\text{eff}}^i}, \quad (1)$$

where  $i$  refers to the different detector configurations (5, 9, 10 and 12 lines),  $\bar{\mu}^{90\%}$  is the average upper limit at 90% CL (calculated using Feldman-Cousins recipe [10]) and  $T_{\text{eff}}^i$  is the livetime for each detector configuration. The average effective area is defined as the equivalent area which would be 100% efficient to detect a neutrino flux and produce the same number of events as the actual detector. Figure 1 shows an example of the effective area for the studied channels.

The optimization is done by scanning the average upper limit for different values of cuts in the search cone angle around the Sun direction ( $\Psi$ ) and the quality parameter assigned by the reconstruction algorithm ( $Q$ ) ([11]). For each neutrino mass and channel, an optimized set of cuts is found.

## 5. Results

Once the selection cuts have been optimized, the signal region is looked at. As shown in Figure 2, no excess over the background has been found, so upper limits in the neutrino flux can be set, as shown in Figure 3 (left). The DarkSUSY package [12] allows to calculate the conversion factor needed to translate the neutrino flux limit into a muon flux limit, shown in Figure 3 (right).

Assuming equilibrium between the neutralino capture rate and the self-annihilation in the Sun, limits on the spin dependent (SD) and spin independent (SI) cross section of the WIMP-proton scattering can be set for the case in which one of them is dominant. These limits are shown in Figure 4 compared to different experimental limits and with the parameter space derived from the CMSSM and MSSM-7 models, where the latest constraints from accelerator experiments have been included (mass of the Higgs  $M_h=125\pm 2$  GeV [13]). A constraint in the neutralino relic density as  $0 < \Omega_{CDM} h^2 < 0.1232$  has also been included.

## 6. Conclusions

The ANTARES data corresponding to 2007-2008 have been used to search for an excess of high energy neutrinos in the Sun's direction, which could indicate annihilation of dark matter particles like neutralinos. The analysis is a binned search that has shown no excess with respect to the expectations from background. Upper limits both in the neutrino and muon flux have been set. Assuming that equilibrium between capture and annihilation has been reached in the Sun, these limits can be translated into limits in the spin dependent and spin independent cross section of the WIMP-proton scattering. The results for spin dependent cross section are particularly competitive with respect to direct search experiments. A comparison with the parameter space allowed by the CMSSM and MSSM-7 models has been shown.

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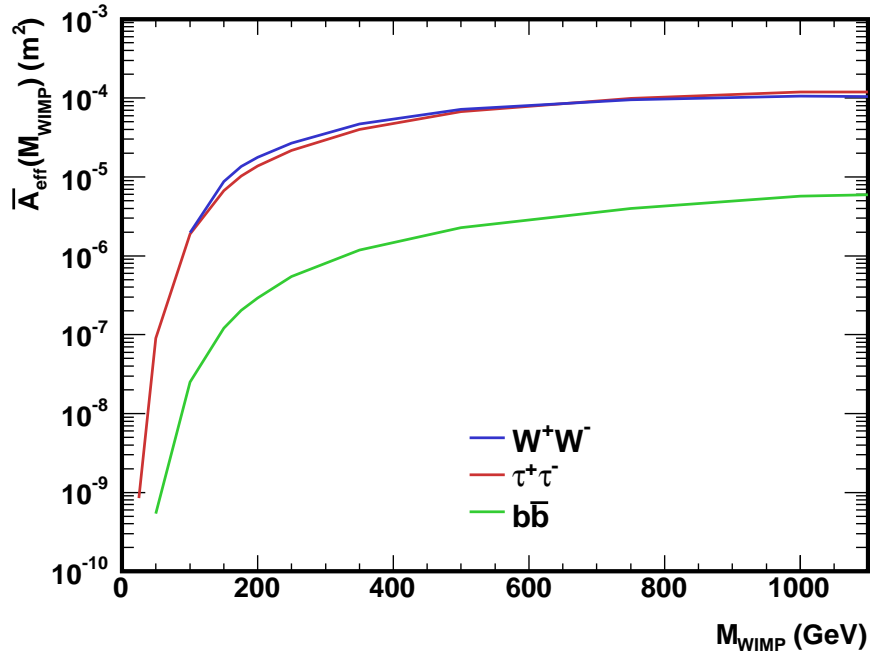


Figure 1: Examples of the averaged effective area  $\bar{A}_{\text{eff}}(M_{\text{WIMP}})$  for the signal of WIMP self-annihilation inside the Sun,  $b\bar{b}$  (green),  $W^+W^-$  (blue) and  $\tau^+\tau^-$  (red) channels. The detector is in a 12 line configuration and the applied cuts in the quality reconstruction parameter and the angular distance with respect to the Sun are  $Q_{\text{cut}} < 1.4$  and  $\Psi_{\text{cut}} < 3^\circ$ , respectively. (Preliminary).



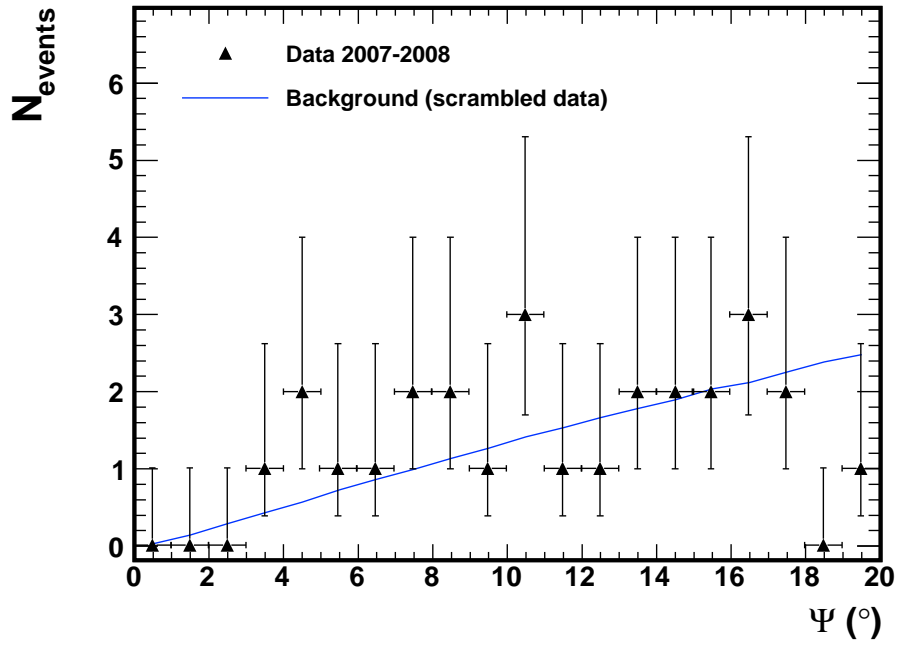


Figure 2: Differential distribution of the angular separation  $\Psi$  of the event tracks with respect to the Sun's direction for the expected background (solid blue line) compared to the data (black triangles). A  $1\sigma$  Poisson uncertainty is shown for each data point. (Preliminary).

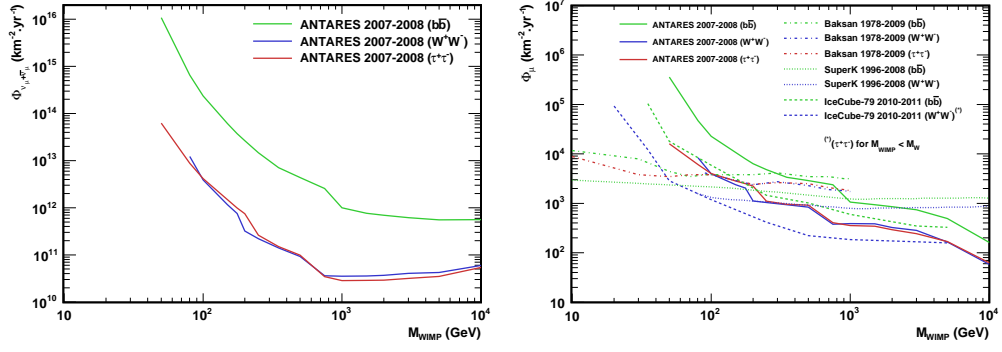


Figure 3: Left: 90% CL upper limits on the neutrino plus anti-neutrino flux as a function of the WIMP mass in the range  $M_{\text{WIMP}} \in [50 \text{ GeV}; 10 \text{ TeV}]$  for the three self-annihilation channels  $b\bar{b}$  (green),  $W^+W^-$  (blue),  $\tau^+\tau^-$  (red). Right: 90% CL upper limit on the muon flux as a function of the WIMP mass in the range  $M_{\text{WIMP}} \in [50 \text{ GeV}; 10 \text{ TeV}]$  for the three self-annihilation channels  $b\bar{b}$  (green),  $W^+W^-$  (blue) and  $\tau^+\tau^-$  (red). The results from Baksan 1978 – 2009 [14] (dash-dotted lines), Super-Kamiokande 1996 – 2008 [15] (dotted lines) and IceCube-79 2010 – 2011 [16] (dashed lines) are also shown. (Preliminary).

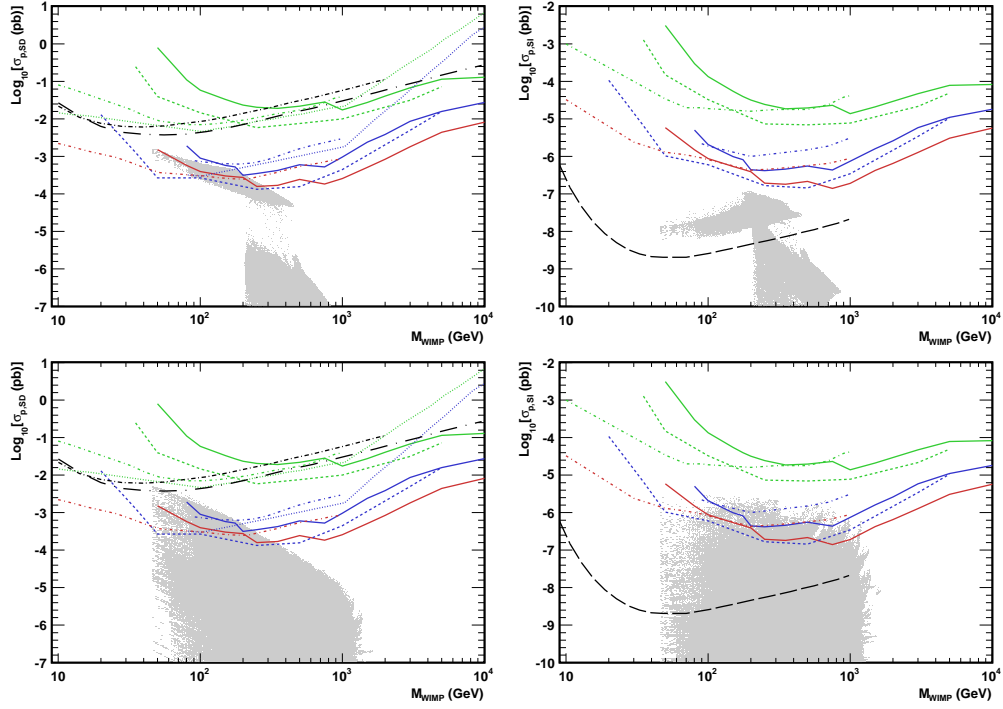


Figure 4: 90% CL upper limits on the SD and SI WIMP-proton cross-sections (plots on the left and right, respectively) as a function of the WIMP mass, for the three self-annihilation channels:  $b\bar{b}$  (green),  $W^+W^-$  (blue) and  $\tau^+\tau^-$  (red), for ANTARES 2007-2008 (solid line) compared to the results of other indirect search experiments: Baksan 1978 – 2009 [14] (dash-dotted lines), Super-Kamiokande 1996 – 2008 [15] (dotted lines) and IceCube-79 2010 – 2011 [16] (dashed lines) and the result of the most stringent direct search experiments (black): SIMPLE 2004 – 2011 [17] (short dot-dashed line in upper plot), COUPP 2010 – 2011 [18] (long dot-dashed line in upper plot) and XENON100 2011 – 2012 [19] (dashed line in lower plot). The results of a grid scan of the CMSSM (upper plots) and CMSSM-7 (lower plots) are included (grey shaded area) for the sake of comparison. (Preliminary)